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Test of a Power Transfer Model for Standardized Electrofishing

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Abstract.—Standardization of electrofishing in waters with differing conductivities is critical when monitoring temporal and spatial differences in fish assemblages. We tested a model that can help improve the consistency of electrofishing by allowing control over the amount of power that is transferred to the fish. The primary objective was to verify, under controlled laboratory conditions, whether the model adequately described fish immobilization responses elicited with various electrical settings over a range of water conductivities. We found that the model accurately described empirical observations over conductivities ranging from 12 to 1,030 μS/cm for DC and various pulsed-DC settings. Because the model requires knowledge of a fish's effective conductivity, an attribute that is likely to vary according to species, size, temperature, and other variables, a second objective was to gather available estimates of the effective conductivity of fish to examine the magnitude of variation and to assess whether in practical applications a standard effective conductivity value for fish may be assumed. We found that applying a standard fish effective conductivity of 115 μS/cm introduced relatively little error into the estimation of the peak power density required to immobilize fish with electrofishing. However, this standard was derived from few estimates of fish effective conductivity and a limited number of species; more estimates are needed to validate our working standard.

The power density produced in water during electrofishing (Monan and Engstrom 1963; Adams et al. 1972) and the efficiency with which power is transferred from water to fish (Kolz 1989) dictate the success of electrofishing. Too little power precludes immobilization of the fish, whereas too much power may immobilize the fish before it can be detected by the collector or may injure the fish (Reynolds 1996). According to Kolz (1989), the effectiveness with which power is transferred to the fish is maximized when the resistivity of the water and the fish match. When the water has more resistance than fish (i.e., the water is less conductive than fish), current tends to flow through the fish; when the fish has more resistance than water (i.e., the fish is less conductive than water), current tends to flow through the water. In either of these mismatches, the power transferred through the circuit into the fish is reduced.

Kolz (1989) proposed a model that adjusted the power transferred to the fish by compensating for the inefficiency of transfer. The model can be used to estimate power to be applied to water with differing conductivities to deliver a constant electric power to fish. Kolz's model is being adopted to standardize electrofishing in management and research applications (e.g., Burkhardt and Gutreuter 1995; Chick et al. 1999). Nevertheless, the model has remained untested, except for the work of Kolz and Reynolds (1989). Accordingly, the first objective of this study was to test whether Kolz's model adequately described fish immobilization responses elicited experimentally with various electrical settings over a range of water conductivities.

Standardization of electrofishing in waters with differing conductivities is critical when this gear is used to monitor temporal and spatial changes in fish assemblages. If Kolz's power model is adequate, it would facilitate standardized electrofishing by allowing control over the amount of power that is transferred to the fish. Fundamental to Kolz's model is the knowledge of water and fish conductivities. Conductivity quantifies the ability of a material to carry an electrical current and is affected by ionic concentration, composition, and temperature. Conductivity of fish is also affected by these variables, but direct measurement is complicated by the variety of electrically dissimilar tissues and fluids. Furthermore, fish conductivity is adjusted by a nervous system that functions akin to a capacitor. Kolz and Reynolds (1989) suggested that the conductivity of fish comprises resistance and capacitive reactance. Kolz (1989) pro-

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posed circumventing measurement of these two components by focusing on ''effective conductivity,'' defined by Kolz (1989) as a measure of the behavioral response of a fish to an electrical stimulus.

The effective conductivity of fish is likely to vary according to species, size, and temperature, among other variables. Because sampling with electrofishing generally targets several species and sizes at once, use of species-specific effective conductivity values may not be practical. However, a generalized value that represents several fish species may be useful, although the merit of such a value would depend on its precision (i.e., the range of fish effective conductivities). Accordingly, the second objective of this study was to gather available estimates of the effective conductivity of fish to examine the magnitude of variation and explore whether an average value could help standardize electrofishing.

Methods

Kolz's model.—Kolz (1989) postulated the following model based on electrical theory:

$$P_f = \frac{P_w}{M_{\text{cp}}}, \tag{1}$$

where P_w = power density applied to the water (μW/cm^3), P_f = power density transferred to the fish (μW/cm^3), and M_{cp} = multiplier for constant power defined by Kolz (1989) as:

$$M_{\text{cp}} = \frac{\left(1 + \dfrac{C_f}{C_w}\right)^2}{4 \cdot \dfrac{C_f}{C_w}}, \tag{2}$$

where C_w = conductivity of water (μS/cm) and C_f = effective conductivity of fish (μS/cm).

Thus, if $C_w = C_f$ in equation (2), then $P_w = P_f$ in equation (1).

The product of water conductivity and voltage gradient squared, P_w, is

$$P_w = C_w\left(\frac{V}{D}\right)^2, \tag{3}$$

where D is the distance between electrodes (cm) and V is voltage. Following Kolz and Reynolds (1989), peak voltage was used to calculate power density (i.e., peak power density).

Electrical treatments.—Six electrical treatments consisting of a range of pulse frequencies were selected from those commonly produced by commercially available electrofishing equipment. Electrical treatments included uninterrupted DC and 110, 60, 30, 20, and 15 Hz pulsed DC (PDC; rectangular pulses). Pulse durations were fixed at 1 ms. All electrical variables were measured within the energized field with a Tektronix THS720A oscilloscope (Tektronix, Inc., Oregon).

Conductivity levels.—Various water conductivity levels were prepared by mixing well water (195 μS/cm) with deionized water or sodium chloride (table salt). Specific conductivity (C_s; μS/cm) and ambient water temperature (T_w) were recorded with a YSI 30/10 FT meter (Yellow Springs Instruments, Ohio). The meter read C_s at specific temperature (T_s; 25°C). However, electrofishing success depends on ambient water conductivity at ambient water temperature. Ambient water conductivity (C_w) was estimated from specific conductivity, specific temperature, and ambient water temperature, as per Reynolds (1996):

$$C_w = \frac{C_s}{1.02^{T_s - T_w}}. \tag{4}$$

Test tank and power source.—All testing was conducted indoors in a polyethylene tank measuring 2.0 m long, 0.5 m wide, and 1.0 m deep. The tank was filled to a depth of 10 cm with well water. The cross-sectional profile of the tank was equipped with two 1.6-cm-thick aluminum plate electrodes positioned 65 cm apart (i.e., D in equation 3), extending above the water surface, perpendicular to the longitudinal axis of the tank. Electricity was supplied to the plates via a Smith-Root 15-D POW unit (Smith-Root, Inc., Washington), modified to allow continuous rather than discrete voltage control, and equipped with supplementary smoothing capacitors to eliminate spikes and reduce ripples at the peak of the pulses. Conditions within the tank produced a homogeneous electrical field with a constant voltage gradient. Homogeneity of voltage gradients within the fields was verified through direct measurements with method 2 of Kolz (1993). Enhancements to the electrofishing unit and the homogeneous field helped reduce irregularities of behavioral responses and thereby generate predictions that were more consistent.

Test fish.—Channel catfish *Ictalurus punctatus* (27–35 cm total length) were used in all tests. This species was used because specimens were readily available from the Mississippi State University Aquaculture Center, where an electrofishing laboratory was assembled and maintained. Concurrent research to identify immobilization thresholds of other species has shown that channel catfish do not exhibit extraordinary behavioral responses and immobilization thresholds (Dolan and Miranda 2003). Before testing, fish were seined from earthen ponds and held in concrete raceways for at least 2 weeks and maintained in good condition on a diet of artificial food. During testing, fish were transferred one at a time to the test tank and confined in the area between the two electrodes. After allowing 3–10 s for the fish to orient, the current was switched on when the fish oriented perpendicular to either electrode. Each fish was exposed to an electrical field for 3 s. The immobilization response (i.e., swimming halted) was recorded in binary form as 0 for no immobilization and 1 if the fish was immobilized. We used 8–15 fish for each water conductivity level and electrical treatment, depending on ease of identifying immobilization threshold. As individuals, fish were treated only once and to a single voltage gradient, but for each conductivity and electrical treatment combination, fish were exposed to voltage gradients stepped from nearly zero to levels 1.5–3 times higher than those needed to achieve immobilization. Step increments in voltage gradients depended on voltage level and electrical treatment and ranged from 1.05× to 2.2× per step. The reactions of each fish were observed and recorded, but fish were also videotaped via a camera positioned over the tank; this allowed review of responses to verify the accuracy of live observations. After testing, fish were transferred to a holding tank and later released into a pond.

Testing Kolz' model.—For each electrical treatment the independent variables peak voltage gradient and C_w level were regressed (logistic regression) against the dependent binary immobilization response. The derived logistic models were used to predict the voltage gradient required for a 0.95 probability of immobilization ($V_{0.95}$/cm) at each C_w level and treatment. To test whether Kolz's model adequately represented observed responses in a range of C_w, we substituted P_w in equation (1) with the equivalent of P_w (equation 3) and substituted M_{cp} with its equivalent (equation 2), so that

$$P_f = C_w\left(\frac{V}{D}\right)^2 \frac{4\cdot\dfrac{C_f}{C_w}}{\left(1 + \dfrac{C_f}{C_w}\right)^2}. \qquad (5)$$

Rearranging equation (5) to solve for voltage gradient (V/D) yielded

$$\frac{V}{D} = \sqrt{\frac{P_f\left(1 + \dfrac{C_f}{C_w}\right)^2}{4C_f}}. \qquad (6)$$

Equation (6) was then fitted according to electrical treatment to the $V_{0.95}/D$ and C_w pairs using nonlinear regression with a multivariate secant iterative method (NONLIN procedure; SAS Institute 1996). Adequacy of Kolz's model was assessed by examining the magnitude and distribution of the residuals generated by fitting equation (6) to the empirical data. Magnitude of residuals was indexed with an R^2 statistic (model 1 of Kvalseth 1985) computed as $1 - \Sigma(y - \bar{y})^2/\Sigma(y - \bar{y})^2$.

Effective conductivity for an average fish.—Regardless of whether C_f values differ statistically among species, sizes, or DC frequencies, one may ask whether an average or standard C_f can help standardize electrofishing. Ideally, separate C_f values would be available for a wide range of target fish species, sizes, and electrical settings, but such specificity would not be helpful in field electrofishing, where multiple species and sizes are usually targeted. Thus, we evaluated the sensitivity of applying a potentially misspecified standard, C_f, on the variability of M_{cp}. When $C_f = C_w$ in equation (2), $M_{cp} = 1$ because the power density in the fish is the same as in the water, but when $C_f \neq C_w$, then $M_{cp} > 1$. We examined how M_{cp} changed relative to C_f for a range of C_w values increasing from 25 to 1,000 μS/cm. We evaluated high and low values of C_f selected from those reported in the literature and from those derived in our study. Thus, to assess the suitability of an average C_f, we evaluated the deviation in M_{cp} caused by a potential error in specifying C_f.

Results

Adequacy of Kolz's Model

In all, the responses of 1,019 channel catfish were included to estimate 93 immobilization thresholds (Figure 1). Ambient water conductivity levels ranged from 12 to 1,030 μS/cm, and ambient water temperatures from 14°C to 21°C. Voltages applied ranged from 3 to 608 V, and voltage gradients from 0.05 to 9.35 V/cm. Levels of $V_{0.95}$/cm estimated with logistic regression ranged from 0.15 to 8.08 (Figure 1).

Values of $V_{0.95}$/cm were related inversely and curvilinearly to ambient water conductivity (Fig-

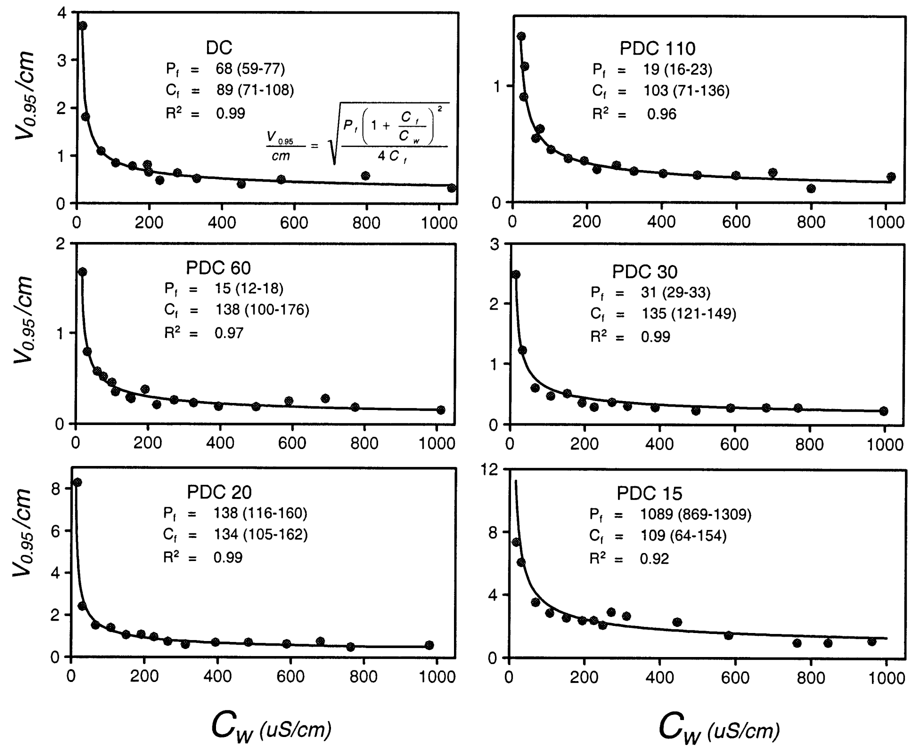

FIGURE 1.—Relation between the voltage gradient required to immobilize 95% of fish ($V_{0.95}$/cm) and conductivity of the water (C_w; μS/cm) for DC electrofishing and five pulsed-DC settings (PDC; Hz). Each point was estimated with 8–15 channel catfish (27–35 cm total length). The nonlinear model fitted to the data (see equation 6) is given in the upper left panel; P_f is the power density transferred to the fish, C_f is the effective conductivity of the fish, and C_w is the conductivity of the water. Values in parentheses represent 95% confidence limits.

ure 1). Equation (6) adequately described the observed relation between C_w and $V_{0.95}$/cm, as indexed by high R^2 values that ranged from 0.92 to 0.99. Residual plots showed no anomalous patterns. The P_f values required for immobilization ranged from 15 to 1,089 μW/cm^3 and were lowest for PDC at 60 and 110 Hz. The P_f values increased dramatically, as pulse frequency decreased, to a high of 1,089 for PDC at 15 Hz. Derived C_f values ranged from 89 to 138 μS/cm and exhibited no obvious trend relative to electrical setting. The 95% confidence limits for C_f in Figure 1 overlapped for all treatments, except for those between DC and PDC at 30 Hz. However, when variances pooled over all C_f estimates were used to compute 95% confidence limits, as prescribed by Zar (1999) for comparisons reliant on confidence interval overlap, all estimates overlapped, indicating that no treatment differences could be detected.

Suitability of an Average Fish Effective Conductivity

An extensive literature search produced few estimates of fish conductivity. Absolute fish conductivities were reported by Haskell (1954; 667 μS/cm), Whitney and Pierce (1957; 787–1,025 μS/cm), Monan and Engstrom (1963; 505–1,266 μS/cm), and Sternin et al. (1972; 319–3,571 μS/cm). These estimates were made by measuring differences in water resistance with and without fish. We disregarded these estimates because they measured absolute conductivity of a carcass, instead of effective conductivity in reference to behavioral responses. A limited number of estimates of effective conductivity were available. Kolz and Reynolds (1989) measured effective conductivity of 6–9-cm goldfish *Carassius auratus* in laboratory tanks. Conductivity of fish was measured at ‘‘stunned immobility,’’ defined as immediate loss of equilibrium; this contrasted with immobilization within 3 s, as defined in our study. Conductivity was 83 μS/cm for goldfish exposed to DC; 156 μS/cm for those at 60 Hz AC; and 145, 160, and 137 μS/cm for those at 50 Hz PDC with pulse widths of 2, 5, and 10 ms, respectively. Using 18–21-cm channel catfish, Jesien and Hocutt (1990) conducted similar testing with various PDC and

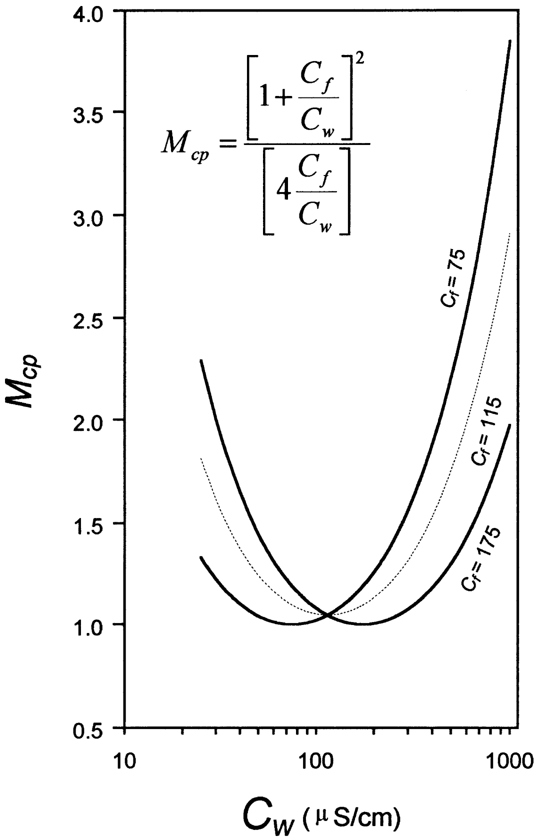

FIGURE 2.—Relation between the multiplier for constant power (M_{cp}) and the conductivity of water (C_w), as tested in the laboratory with channel catfish. The M_{cp} was calculated for effective conductivities of fish (C_f) of 75 and 175 μS/cm. A C_f of 115 was found to split the two curves about evenly.

AC settings but included only three water conductivities, not enough to properly fit equation (6). Liu (1990) reported voltage gradients required to elicit a fright response in silver carp *Hypophthalmichthys molitrix* and bighead carp *H. nobilis* treated with 50-Hz AC at seven water conductivities. Equation (6) adequately fit their data ($R^2 \geq 0.89$) and identified C_f values of 56 μS/cm for bighead carp and 96 μS/cm for silver carp. Given these distributions and those measured in our study, fish effective conductivity values ranging from 75 to 175 were selected for modeling M_{cp}.

The distribution of M_{cp} relative to C_w was characterized by U-shaped curves that bottomed at 1 when C_w equaled C_f (Figure 2). The vertical distance between the U-shaped curves indicated the potential error resulting from incorrectly specifying C_f and, thus, M_{cp}. The error increased as C_w values diverged from the 100–150 span. The C_f = 75 μS/cm and C_f = 175 μS/cm U-shaped curves intersected at C_w = 115 μS/cm, corresponding to a C_f that divided the distance between the curves roughly in half (Figure 2). Thus, in practical applications an average C_f of about 115 would result in the least M_{cp} error forced by a mistaken C_f. If C_f = 115 was used to compute M_{cp} and estimate P_w required to produce a consistent P_f over waters with 100 and 400 μS/cm, the M_{cp} would be 1.05 for 100 μS/cm and 1.53 for 400 μS/cm (Figure 2). However, if C_f was mistaken and the true value was 175 (about 50% higher), the M_{cp} would be 1.08 for 100 μS/cm and 1.18 for 400 μS/cm. This discrepancy in C_f would have produced differences in M_{cp}, and therefore P_f, of 2.9% at 100 μS/cm and 22.9% at 400 μS/cm. In general, this misestimation resulted in a 5% or less M_{cp} error in waters with conductivities of 90–145 μS/cm, 10% or less in conductivities of 70–187 μS/cm, and less than 30% in conductivities of 25–750 μS/cm.

Discussion

Kolz's (1989) model adequately fitted the empirical C_w and $V_{0.95}$ matched pairs, suggesting that the model can help standardize electrofishing in differing conductivities. The R^2 values for the regressions were higher than 0.95, except for PDC at 15 Hz. At that setting, fish exhibited a vigorous forced swimming behavior that made it hard to assert whether the fish had been immobilized within 3 s, even after reviewing recorded videos. This difficulty probably reduced the precision of observations. Experimental temperatures that ranged 7°C could have introduced additional but trivial variability because the models fitted already accounted for most of the variability (i.e., R^2 values ranged from 0.92 to 0.99). According to Whitney and Pierce (1957) temperature influences fish absolute conductivity and thereby possibly effective conductivity. Overall, variability around regression parameters was minimal and composed of experimental error rather than model lack of fit. Although our test of Kolz's model has implications for field sampling, testing would have been difficult under field conditions because the heterogeneous voltage gradient would have introduced additional error to testing and estimation.

Immobilization within 3 s was chosen as the reaction to identify a threshold response to electricity. We suspect that equivalent C_f values could have been derived had we chosen contiguous behavioral responses that have different P_f thresholds (e.g., fright, immobilization within 1 s). Use of other behavioral responses would affect the P_f parameter in equation (6) (e.g., a lower P_f for fright response or a raised P_f for immobilization within 1 s) but should not change the C_f parameter, unless the neural response is substantially different. In this regard, Kolz and Reynolds (1989) documented that estimates of C_f made at two threshold responses were similar and deviated mainly because of measurement error.

Estimated values of P_f were related to pulse frequency, but those of C_f were not. The amount of peak power needed to immobilize fish was low for high-frequency settings and increased as frequency decreased. This effect may be attributed to longer off time associated with low-frequency waveforms that allow muscles more time to relax before stimulating them with the next pulse of electricity, and thus, more time or higher peak power density is required to immobilize fish (Vibert 1967; Bird and Cowx 1990). This pattern does not account for the P_f of DC, which was intermediate between a PDC of 20 and 30 Hz. However, the mechanism that produces immobilization is thought to be different for DC. The fluctuating current of PDC reportedly produces stimulations of nervous fibers that lead to immobilization via cramping of muscles, whereas the continuous current of DC either inhibits or overexcites body cells and muscle fibers but does not affect the nerve fibers (Lamarque 1967; Vibert 1967). A relationship between C_f and pulse frequency was expected given that effective conductivity integrates tissue resistance and capacitive reactance, which may respond differently to diverse pulse patterns. The absence of such a relationship may reflect the small range in C_f, the inability to measure C_f more precisely, or both. Kolz and Reynolds (1989) found no relationship between C_f and pulse widths of 2, 5, and 10 ms delivered by a PDC of 50 Hz. However, they reported DC resulted in the lowest effective conductivity, and noted a positive relation between frequency and conductivity (not tested statistically). Although our results also showed that DC was associated with the lowest C_f value, C_f estimates did not differ statistically among treatments.

The question of whether an effective conductivity for an average fish—115 μS/cm being suggested—would partially standardize electrofishing was considered by evaluating the sensitivity of M_{cp} to a ±50% estimation error in fish effective conductivity. In general, the effect of misestimating C_f on M_{cp} was less than 30% in conductivities of 25–750 μS/cm. These deviations are relatively small when compared to variability in voltage gradients. In a typical electrofishing field, voltage gradient ranges from 0.01 to 2 V/cm or higher (Kolz 1993). In this context, the effect of a misestimated C_f would not seriously impede efforts to standardized electrofishing over waters with different conductivities. Our study showed that a 115-μS/cm standard for effective conductivity introduced relatively little error in estimating standard power. However, that standard was derived from the few estimates of effective conductivity available for a limited number of fish species; more estimates are needed to validate our working standard.

Kolz's power transfer model adequately predicted the peak power density required to elicit immobilization over a wide range of water conductivities. The model can help standardize electrofishing by allowing use of fixed peak power over waters with diverse conductivities, reducing variability resulting from inconsistent application of electrical power. Standardization can be achieved through equation (1). Beginning with a P_f recognized as the target, the user adjusts voltage to achieve a P_w that yields the target P_f under existing C_w conditions. Target P_f values may be determined experimentally or empirically. Under controlled experimental conditions, Dolan and Miranda (2003) identified P_f thresholds required to immobilize eight fish species of diverse sizes. Those thresholds can be reproduced in the field by managing power applied to the water (methods described by Novotny 1990; Kolz 1993). Alternatively, Burkhardt and Gutreuter (1995) standardized P_f empirically by fixing P_f at a level identified to yield superior catch rates. Although partial standardization occurs when operators of electrofishing equipment regulate voltage or amperage to adjust for local conditions and maximize catch rates, Kolz's model provides a scientific method that removes operator bias from the standardization procedure. Nevertheless, because a multiplicity of factors affect catch variability (Reynolds 1996), Kolz's model cannot solve all standardization conundrums posed by electrofishing.

Standardization of electrofishing can help reduce the variability of survey data and potentially reduce injury to fish. With no standardization, differences among collections can be partially attributed to disparities in electrofishing efficiency and not primarily to disparities in fish abundance, population structure, or fish assemblage composition. Adoption of a standard power transfer over ranging conductivities should be central to standardization programs. In one study, standardization of power transfer improved predictability of electrofishing catch rates by about 15% (Burkhardt and Gutreuter 1995). Moreover, injury to fish attributed to electrofishing can often be traced back to exposure to excessive power levels (Snyder 1995). Thus, standardization of power transferred to fish can also minimize injury and mortality. Nevertheless, because electrofishing is an active capture method applied to changing microenvironments, complete standardization is probably impossible with present technology, but standardization of controllable variables is still advisable.

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References

Adams, W. J., D. J. Behmer, and W. O. Weingarten. 1972. Recovery of shocked common shiner, *Notropis cornutus*, related to electric energy Transactions of the American Fisheries Society 101:552–555.

Bird, D., and I. G. Cowx. 1990. The response of fish muscle to various electric fields. Pages 27–33 *in* I. G. Cowx and P. Lamarque (1990).

Burkhardt, R. W., and S. Gutreuter. 1995. Improving electrofishing catch consistency by standardizing power. North American Journal of Fisheries Management 15:375–381.

Chick, J. H., S. Coyne, and J. C. Trexler. 1999. Effectiveness of airboat electrofishing for sampling fishes in shallow, vegetated habitats. North American Journal of Fisheries Management 19:957–967.

Cowx, I. G., and P. Lamarque, editors. 1990. Fishing with electricity. Fishing News Books, Oxford, UK.

Dolan, C. R., and L. E. Miranda. 2003. Immobilization thresholds of electrofishing relative to fish size. Transactions of the American Fisheries Society 132: 969–977.

Haskell, D. C. 1954. Electrical fields as applied to the operation of electric fish shockers. New York Fish and Game Journal 1:130–170.

Jesien, R., and R. Hocutt. 1990. Method for evaluating fish response to electric fields. Pages 10–18 *in* I. G. Cowx and P. Lamarque (1990).

Kolz, A. L. 1989. A power transfer theory for electrofishing. U.S. Fish and Wildlife Service Technical Report 22:1–11.

Kolz, A. L. 1993. In-water electrical measurements for evaluating electrofishing systems. U.S. Fish and Wildlife Service Biological Report 11.

Kolz, A. L., and J. B. Reynolds. 1989. Determination of power threshold response curves. U.S. Fish and Wildlife Service Technical Report 22:15–23.

Kvalseth, T. O. 1985. Cautionary note about R^2. American Statistician 39:279–285.

Lamarque, P. 1967. Electrophysiology of fish subject to the action of an electric field. Pages 65–92 *in* R. Vibert, editor. Fishing with electricity, its application to biology and management. Fishing News Books, Oxford, UK.

Liu Qi-Wen. 1990. Development of the model SC-3 alternating current scan fish driving device. Pages 46–50 *in* I. G. Cowx and P. Lamarque (1990).

Monan, G. E., and D. E. Engstrom. 1963. Development of a mathematical relationship between electric-field parameters and the electrical characteristics of fish. U.S. Fish and Wildlife Service Fishery Bulletin 63:123–136.

Novotny, D. W. 1990. Electric fishing apparatus and electric fields. Pages 34–88 *in* I. G. Cowx and P. Lamarque (1990).

Reynolds, J. B. 1996. Electrofishing. Pages 221–253 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques. American Fisheries Society, Bethesda, Maryland.

SAS Institute. 1996. SAS statistics user's guide. SAS Institute, Cary, North Carolina.

Snyder, D. E. 1995. Impacts of electrofishing on fish. Fisheries 20(1):26–39.

Sternin, V. G., I. V. Nikonorov, and Y. K. Bumeister. 1972. Electrical fishing, theory and practice. English translation from Russian by E. Vilim. Israel Program for Scientific Translations. Ketel Publishing House Jerusalem Ltd., Jerusalem, Israel.

Vibert, R., editor. 1967. Fishing with electricity, its application to biology and management. Fishing News Books, Oxford, UK.

Whitney, L. V., and R. L. Pierce. 1957. Factors controlling the input of electrical energy into a fish (*Cyprinus carpio* L.) in an electrical field. Limnology and Oceanography 2:55–61.

Zar, J. H. 1999. Biostatistical analysis, 4th edition. Prentice-Hall, Upper Saddle River, New Jersey.